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Study on construction and quantification of evaluation index system of mine ventilation system

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Abstract

Mine ventilation system which was the important constituent of coal mining system ensured the safety production as critical measures. Construction and quantification of evaluation index system for mine ventilation system was the basis and standard of comprehensive evaluation of system's defect. This paper began with hazard factors which caused ventilation accident, investigated the direct and indirect reasons, and then carried on a qualitative analysis of Fault Tree. According to analysis results, an evaluation index system of ventilation system was constructed and the index was also quantified by use of AHP. Since that existing index system was improved and supplemented, it is supposed to improve the operational capability and rationality of daily management as well as safety evaluation of mine ventilation system.

Keywords: mine ventilation system; FTA; AHP; evaluation index system

1. Introduction

Nowadays, coal mine gas accidents happened frequently in China which has been delayed the coal industry development. Ventilation is the basis of gas treatment, stable and reliable ventilation system should be established in mining working face and other places in mine. However, due to a number of impact factors, to measure the quality of mine ventilation system has a lot of indicators, which is hard to handle. Therefore, the safety evaluation of mine ventilation system is an important and complicated task. It is very important to improve the safety management of mine ventilation system if this task can be done [1]. Meanwhile, existing index systems are complicated, and the meaning of different indicators overlaps, with poor interoperability. Up to now, there is not a common set of evaluation index system [2]. Therefore, the paper believes that should have innovative thinking and technical means to study on index system and explore it. In this paper, the evaluation index system was built on the basis of analysis risk factors of mine ventilation system by FTA, and then quantified the various indicators. The conclusions to improve and standardize the evaluation index system of the ventilation system played a positive role and had practical significance.

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2. The basis of evaluation indicators determination

Construction and quantification evaluation indicators are the foundations and the key of evaluation of mine ventilation system directly affect the evaluation results. Evaluation indicator determined must be justified, neither flashy nor too monotonous. The paper compilation a Fault Tree according to the hazard analysis of the mine ventilation system, and quantified the various indicators based on the results of Fault Tree Analysis by using of Analytical Hierarchy Process (AHP).

2.1. Fault tree compilation

In summary, the mine ventilation system is provided by the ventilation mode, ventilation airflow and networks, ventilation method as well as the ventilation management system and basic facilities. According to the analyses of coal-mine accidents over years, the paper finds out that all the coal mine accidents happened caused by defects of the ventilation system, mainly are:

- Reasonableness of ventilation mode;
- Mine airflow failed;
- Reliable power ventilation system;
- Mismanagement of ventilation system and inadequate safety facilities.

According to the accident-induced, put the causes of accidents into the conditions of accident as much as possible the conditions and set them out. According to the logical relationship between the cause and the effect, combine the cause and the effect in a diagram (see Fig. 1), thereby complete the establishment of the FTA.

2.2. Tree fault tree analysis

Fault Tree is a directed logic tree which describes incidents from result to reason. Use of the tree can be found not only lead to the direct cause of the accident, but also to reveal the underlying factors of accidents, so provide a reasonable basis to determine evaluate indicators [3]. This Fault Tree carries out a comprehensive analysis of hazards from entire ventilation system in accordance with the identified identification unit, through the analysis the paper found that the Fault Tree has 13 or gates more than and gates, which only have 3. Therefore, the Fault Tree with a higher risk level, using least path set for analysis will be more convenient. The structure functions of its success tree as follows:

$$\begin{aligned}
 T' &= x'_1 A_1' A_2' A_3' A_4' \\
 &= x'_1 A_5' A_6' A_7' A_8' A_9' A_3' A_4' \\
 &= x'_1 A_5' A_6' A_{10}' A_{11}' A_8' A_9' A_3' A_4'
 \end{aligned} \tag{1}$$

Then, substitute and decompose the structure functions with Boolean algebra, so as to get the least path set of 8 groups, are as follows:

$$\begin{aligned}
P_1 &= \{x_1, x_2 \cdots x_{15}, x_{16}, x_{17}, x_{18}, x_{20}, x_{22}, x_{25} \cdots x_{50}\} \\
P_2 &= \{x_1, x_2 \cdots x_{15}, x_{16}, x_{19}, x_{20}, x_{22}, x_{25} \cdots x_{50}\} \\
P_3 &= \{x_1, x_2 \cdots x_{15}, x_{16}, x_{17}, x_{18}, x_{21}, x_{22}, x_{25} \cdots x_{50}\} \\
P_4 &= \{x_1, x_2 \cdots x_{15}, x_{16}, x_{19}, x_{21}, x_{22}, x_{25} \cdots x_{50}\} \\
P_5 &= \{x_1, x_2 \cdots x_{15}, x_{16}, x_{17}, x_{18}, x_{20}, x_{23}, x_{24}, x_{25} \cdots x_{50}\} \\
P_6 &= \{x_1, x_2 \cdots x_{15}, x_{16}, x_{19}, x_{20}, x_{23}, x_{24}, x_{25} \cdots x_{50}\} \\
P_7 &= \{x_1, x_2 \cdots x_{15}, x_{16}, x_{17}, x_{18}, x_{21}, x_{23}, x_{24}, x_{25} \cdots x_{50}\} \\
P_8 &= \{x_1, x_2 \cdots x_{15}, x_{16}, x_{19}, x_{21}, x_{23}, x_{24}, x_{25} \cdots x_{50}\}
\end{aligned} \tag{2}$$

From the path set can be judged, there are eight kinds of ways to ensure that accidents would not occur. Concentrate derived from the Path, ventilation mode, ventilation airflow, ventilation power systems, ventilation safety management and safety facilities to ensure the safety of the ventilation system are equally important. The intermediate events and basic events of Fault Tree will play an important role for index system construction in the below text.

3. Construction and quantification of evaluation index system on mine ventilation system

3.1. Evaluative indicators determination

According to the qualitative analysis of Fault Tree of mine ventilation system defect, the index system is divided into 5 criteria layers, which are:

- Reasonableness of ventilation mode;
- Reasonableness of the ventilation network;
- Qualified degree of mine airflow;
- Reliability of power ventilation system;
- Normalization of ventilation system management and facilities.

3.1.1. The reasonableness of ventilation mode

(1) Reasonableness of ventilation modes I_1 : Basic reason event (the inaptitude for ventilation mode x_1), is taken to evaluate reasonableness of the ventilation mode in the practical application (central, diagonal-type and mixed type) that the mine ventilation system is designed and approached.

3.1.2. Reasonableness of the ventilation network

(2) Rationality of network distribution I_2 : Basic reason events (the confusion tunnel x_2 , indiscriminate mining and digging x_3 , no independent whole ventilation system x_{13}), a reasonable roadway layout is conducive to the establishment of a scientific, rational, stable and reliable ventilation system; is conducive to control gas and coal dust and fire; is conducive to improve the effective airflow rate in mining area; is conducive to enhance the response capacity of the mine. The three basic reasons occurred or not reflect the distribution of ventilation network whether is reasonable. The improper layout of the network would lead to an unreasonable ventilation system, such as unreasonable ventilation velocity, ventilation quality and ventilation quantity.

(3) Rationality of roadway resistance force I_3 : Basic reason event (high tunnel resistance x_4), the tunnel resistance which be measured by equivalent orifice is too high so that ventilation velocity can not meet *coal mine safety regulation* requirement.

(4) Rationality of series, parallel, and diagonal structure ventilation I_4 : Basic reason events (incompatible series, parallel, and diagonal structure ventilation x_6 , drifting tunnel connect to others in random x_7), a direct impacted on the volume of mine natural distribution if the incident occurred. The rationality of series, parallel, and diagonal structure ventilation selection play a decisive role on the wind distribution and ventilation velocity.

(5) Rationality of air pressure and return deployment I_5 : Basic reason events (the inaptitude of return air regulation x_8 , the inaptitude of air return tunnel x_9), in order to make air volume distributed according to need, the wind pressure regulations and return air deployment measures needs to be taken after the wind natural distribution, which made wind volume and wind velocity meet roadway design requirements.

(6) Normalization of ventilation structure I_6 : Basic reason events (air door and break-wind wall air leakage x_{10} , unreasonable air door, air bridge x_{11} .) Normalization and rationality of the air door, air bridge, and break-wind wall setting determines whether the quality of the ventilation network and, ventilation resistance force meets the *coal mine safety regulation* requirements or not.

3.1.3. Qualified degree of mine airflow

(7) Qualified degree of air velocity on roadway I_7 : Intermediate event (unqualified ventilation velocity A_5), the intermediate events have 12 basic events (Fig. 1 shows). Any basic event happened would result in unreasonable wind velocity, and the mine with the wind velocity too large or too small, will affect the underground environment where the staff work in.

(8) Qualified degree of used air quantity I_8 : Intermediate event (unqualified ventilation quantity A_6), the intermediate events have 12 basic events (Fig. 1 shows). Improper air controlling, goaf close is not timely and serious leakage will lead to unreasonable mine air volume, which resulting in failure of ventilation of the ventilation system.

(9) Qualified degree of effective wind rate I_9 : Basic reason events (low effective wind x_{15} , low rate of effective wind x_{16}), not only reflects the utilization of the mine air volume, but also reflects reasonable situation and its leakage situation of the underground ventilation facilities.

(10) Qualified degree of wind quality I_{10} : Intermediate events (gas exceed A_{12} , dust exceed A_{13}), the gas and dust concentration posed a serious threat to security if the failure in ventilation, unreasonable series structure ventilation or failure in dust removal.

(11) Suitability degree of thermal environment I_{11} : Basic reason events (no thermo control x_{23} , thermo control measures invalid x_{24}), Normal event (geothermal x_{22}), the existence of mine internal geothermal circumstances, and the invalid temperature control measure will lead to unsuitable for mining. The fitness of thermal environment such as temperature, humidity, and so on, directly affects the miners' productivity, physical and mental health [4].

3.1.4. Ventilation power system

(12) Rationality of ventilation style I_{12} : Basic reason event (incorrect selection of ventilator type x_{27}), the selection of ventilation type includes horsepower of fan, air pressure, air quantity, and type of ventilation. Selection of axial-flow or centrifugal determines what ventilation pattern is forced, exhaust, or hybrid ventilation.

(13) Integration of safety facility in machine room I_{13} : Basic reason event (no a full set of device in machine room such as ammeter of water column x_{25} , no alternate ventilation x_{26}), *regulation* requires there must be alternate ventilation, water column, voltmeter, wattmeter, bearing thermometer, and so on.

(14) Qualified degree of ventilator performance I_{14} : Basic reason events (overly leakage of ventilator heap stead x_{28} , overly low performance of ventilator x_{29} , and ventilator degeneration overly x_{30}) play a critical role in determining ventilator performance, such as static pressure, air quantity, input power, and efficiency of static pressure.

(15) Qualified degree of air reversing facility I_{15} : Basic reason event (no air reversing device x_{31} , no periodic check of air reversing device x_{32} , and air reversing exercise is not in line with procedure x_{33}), the time and rate of air reversing should be met to the requirement of *regulation*. If one of basic reason events happens, that would cause disqualification of ventilator.

(16) The reliability of partial ventilation system I_{16} : Basic reason event (unreasonable selection of style of portion ventilation x_{34} , unreasonable selection of type of portion ventilator x_{35} , unreasonable type and parameter of wind sleeve x_{36} , overly leakage duct air x_{37}). Those result from selection of ventilator and wind sleeve and set of parameter. Basic reason event (non-compliance motor protection of wind electricity closed-cycle control x_{38}) causes disqualification of safety device of partial ventilator.

3.1.5. Management and facility of ventilation

(17) Integrity of figure for ventilation system I_{17} : Basic reason event (no detailed and formal figures of ventilation

system x_{39}) is the important technology information for safety management of ventilation.

(18) Integrity of safety institution for ventilation I_{18} : Basic reason events (no making or filling in ventilation tables x_{40} , inadequate safety institution of ventilation x_{47}) are evaluation of safety institution.

(19) Qualified degree of ventilation monitoring I_{19} : Basic reason events (no periodic roadway resistance check x_{41} , no periodic check of ventilator performance x_{42}) imply that periodic check of ventilation is a fine way of ensuring safety.

(20) Qualified degree of regulation-abiding worker I_{20} : Basic reason events (worker violation deliberately with low quality x_{43} , intermittent work of ventilator x_{44} , worker open and close ventilation door at random x_{45}) mean that the rate of human violation deliberately.

(21) Qualified degree of special worker I_{21} : Basic reason event (undocumented worker of ventilation x_{46}) shows that special workers can make sure safety ventilation with certification and maintain safety lever of work.

(22) Qualified degree of safety facility for fire fighting I_{22} : Basic reason events (no fire water supply pipeline in tunnel x_{48} , no gas self-test device x_{49} , no permanent monitoring station in inlets x_{50} , no permanent monitoring station in back tuyere x_{51}) tell that whether the safety device is integral determines reliability and effective result of fire protection in roadway.

3.2. The weight of the quantitative indicators

Analytical Hierarchy Process (AHP) is raised by Thomas L• Saaty (1970), a well-known operations researcher, a Professor of Pittsburgh University. With this method, factors of the question can be divided into layers of target, criteria, and program levels. Relevant factors affecting the overall performance would be analyzed at different levels. In accordance with the best principles—the indicators of lower targets subordinate to the upper, the evaluation methods of hierarchy structure is determined (concrete steps are limited). Mine ventilation system which is based on fuzzy strong features can be applied for the quantification of weight of indicators.

3.2.1. Quantification of target layer to criteria layer

Combined with analysis of expert advice on the structure and accident information of mine ventilation, (A- G_i) ($i=1\sim5$) the matrix is determined, as shown in Table 1. By using of MATLAB software, the maximum eigenvalue is determined, $\lambda_{\max} = 5.0681$.

$$CI = (\lambda_{\max} - n) / (n - 1) = (5.0681 - 5) / (5 - 1) = 0.0170 \quad (3)$$

Check RI table, the value of 5-order matrix for the RI is 1.12, so:

$$CR = \frac{CI}{RI} = \frac{0.0170}{1.12} = 0.015 < 0.1 \quad (4)$$

The result gets through consistency check.

Table 1. Judgment matrix for mine ventilation system A- G_i

Mine ventilation system A	G_1	G_2	G_3	G_4	G_5	W_i
Rationality of ventilation style G_1	1	1/5	1/4	1/4	1/2	0.0618
Rationality of ventilation network G_2	5	1	3	2	4	0.4185
Rationality of mine airflow G_3	3	1/3	1	1/2	2	0.1599
Ventilation power systems G_4	4	1/2	2	1	3	0.2625
Management of Ventilation and facility G_5	2	1/4	1/2	1/3	1	0.0973

3.2.2. Quantification of criteria layer to criteria program layer

(1) The judgment matrix of rationality of ventilation network is constructed though expert comparative method

(G_2-I_i) ($i=2\sim6$), as shown in Table 2. The largest eigenvalue $\lambda_{\max}=5.0737$.

$$CI = (\lambda_{\max} - n) / (n - 1) = (5.0737 - 5) / (5 - 1) = 0.0246 \quad (5)$$

Check RI table, the value of 5-order matrix for the RI is 1.12, so:

$$CR = \frac{CI}{RI} = \frac{0.0246}{1.12} = 0.022 < 0.1 \quad (6)$$

The result gets through consistency check.

Table 2. Mine ventilation system to determine the matrix G_2-I_i

Rationality of ventilation network G_2	I_{21}	I_{22}	I_{23}	I_{24}	I_{25}	W_{2i}
Rationality of network distribution I_{21}	1	5	3	2	4	0.4230
Rationality of roadway resistance force I_{22}	1/5	1	1/2	1/3	1/2	0.0723
Rationality of series, parallel, and diagonal structure ventilation I_{23}	1/3	2	1	1/2	2	0.1507
Rationality of air pressure and return employment I_{24}	1/2	3	2	1	3	0.2533
Normative of ventilation structure I_{25}	1/4	2	1/2	1/3	1	0.1007

Similar calculation as follows:

(2) Rationality of mine airflow (G_3-I_i) ($i=7\sim11$)

$$CR = CI/IR = 0.0204/1.24 = 0.016 < 0.1 \quad (7)$$

Eigenvector

$$W_{3i} = [0.3854 \ 0.1626 \ 0.2531 \ 0.0380 \ 0.0983 \ 0.0627]^T \quad (8)$$

(3) Ventilation power system (G_4-I_i) ($i=12\sim16$)

$$CR = CI/IR = 0.0368/1.12 = 0.033 < 0.1 \quad (9)$$

Eigenvector

$$W_{4i} = [0.0723 \ 0.0446 \ 0.4443 \ 0.1457 \ 0.2932]^T \quad (10)$$

(4) Management of ventilation and facility (G_5-I_i) ($i=17\sim22$)

$$CR = CI/IR = 0.0228/1.24 = 0.018 < 0.1 \quad (11)$$

Eigenvector

$$W_{5i} = [0.1196 \ 0.1860 \ 0.3005 \ 0.0553 \ 0.0381 \ 0.3005]^T \quad (12)$$

3.2.3. The overall consistency check

The weight of the indicators for evaluation index system model (Fig. 2) is constructed by AHP calculation.

$$CR = \frac{\sum_{i=1}^5 w(G_i)CI_i + \sum_{j=1}^{22} w(I_{ij})CI_j}{\sum_{i=1}^5 w(G_i)RI_i + \sum_{j=1}^{22} w(I_{ij})RI_j} = \frac{0.1073}{5.62} = 0.0191 < 0.1 \quad (13)$$

Therefore, the overall gets through consistency check.

3.3. Construction of evaluation index system

According to Fault Tree, through five criteria layers—the rationality of ventilation style, the rationality of ventilation network, the rationality of mine airflow, ventilation power systems, management of mine ventilation and facility, twenty-two evaluation indexes is identified. And then, the evaluation index system for mine ventilation system was constructed (Fig. 2).

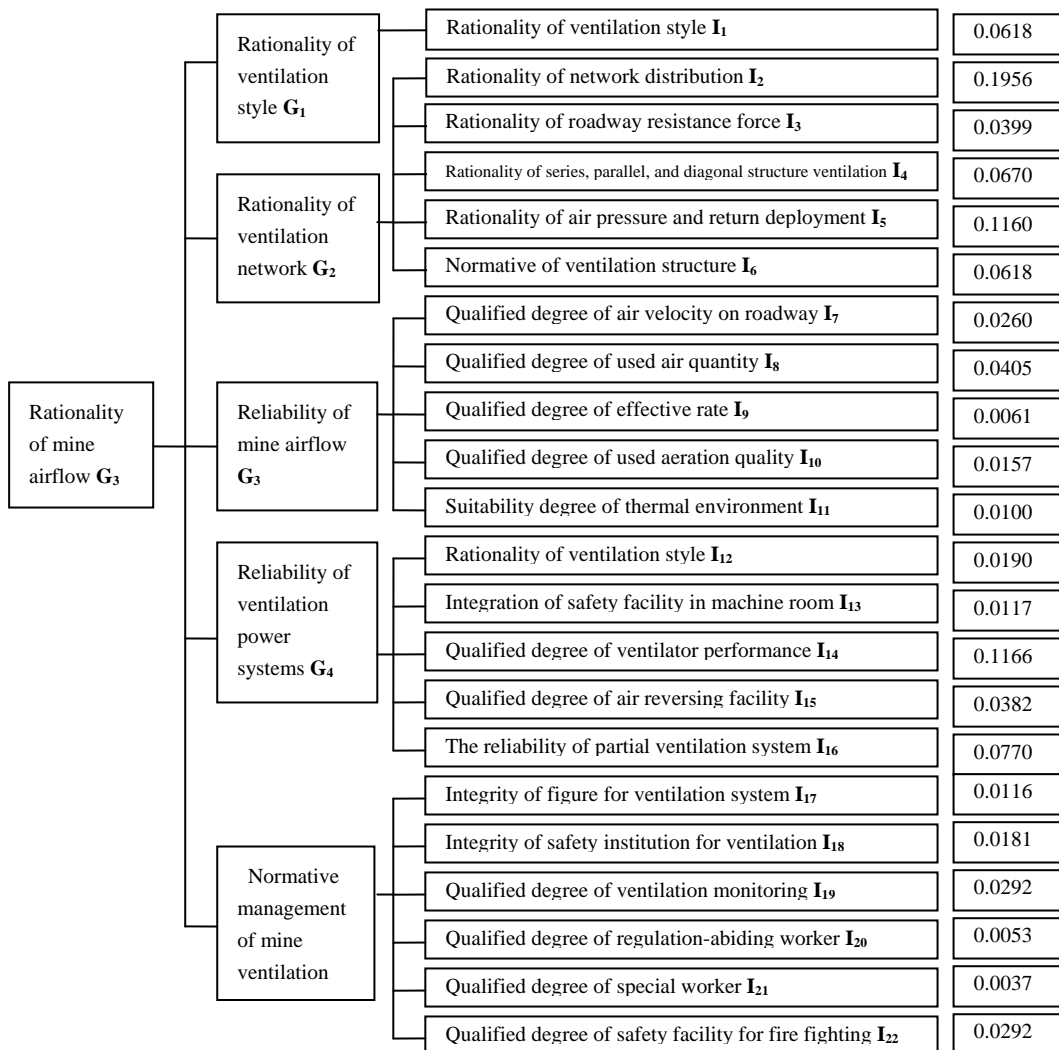


Fig. 2. Model of evaluation index system and weight quantification for mine ventilation system

4. Conclusions

1) Based on Fault Tree Analysis of mine ventilation risk factors, combination of the data and reference literature, identification of five evaluation criteria and twenty-two evaluation indicators, a set of reasonable, integral,

comprehensive, and systematic safety evaluation index system for the ventilation system was constructed;

2) The evaluation system was improved and supplemented, including selection of ventilation, air pressure, a reasonable degree of deployment for wind back, the level of ventilator performance, and integrity of ventilation system figures;

3) Formed safety evaluation index through which safety evaluation analysis can be done, is feasible, scientific and full-grounded. That can be used more effectively in actual production [4].

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